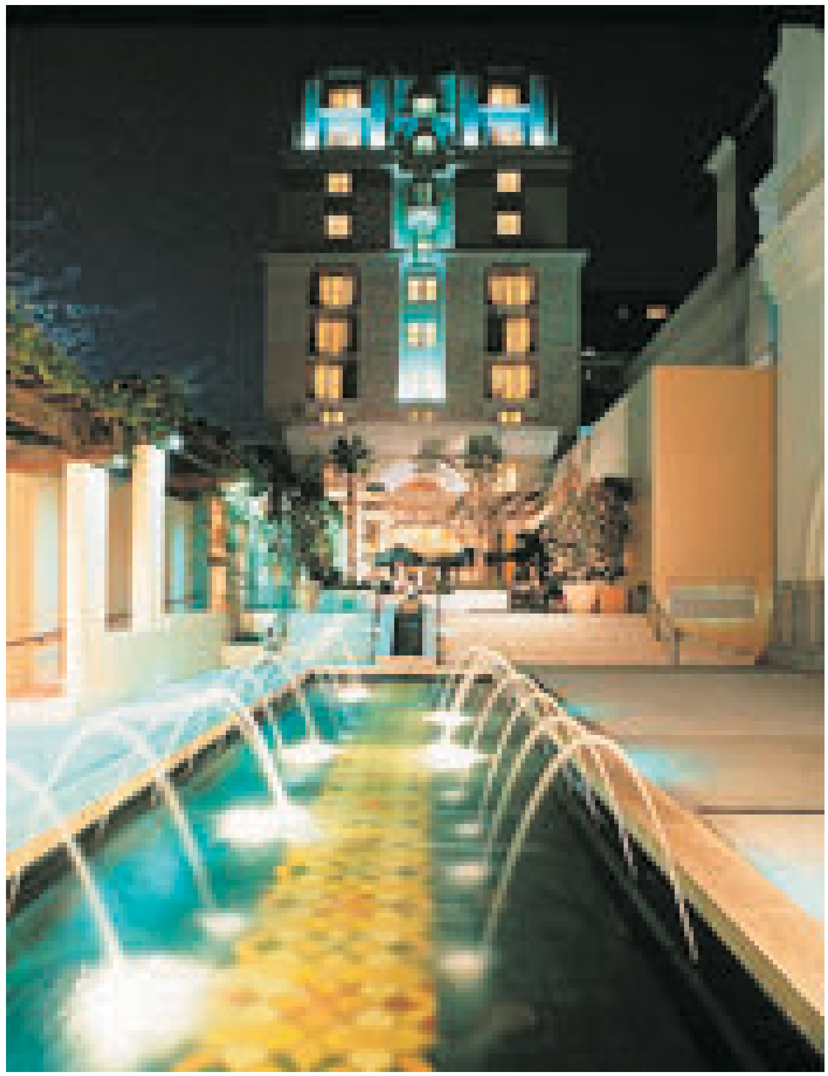
IEEE CAS Workshop on Wireless Communications and Networking

Power Efficient Wireless Ad Hoc Networks



September 5-6, 2002
at
Doubletree Hotel,
Pasadena, California

Welcome *to the 5th IEEE Circuits and Systems Society Workshop on Wireless Communications and Networking, organized by the Jet Propulsion Laboratory and held at the Doubletree Hotel, Pasadena, CA, September 5-6, 2002. Some 80 researchers from around the world will be attending a program of 34 high quality papers and posters as well as an opening address and two keynote presentations. At the conclusion of the formal program, there will be a panel discussion with highly respected panelists from industry addressing commercial interests in wireless ad-hoc networks. In addition to the above, there will be hardware/software demonstrations of ongoing research efforts in Southern California universities.*

We are very proud to be hosting the workshop in Pasadena and, in view of this, have arranged a tour of JPL facilities on the afternoon of the first day of the workshop. It is the goal of this workshop to provide, through open informal discussion, an environment for all the participants to exchange their ideas and experiences thereby promoting future cooperation amongst themselves as well as with our organization.

On behalf of the workshop, I would like to take this opportunity to acknowledge the support and sponsorship of DESCANSO, the Deep Space Communications and Navigation Systems Center of Excellence, which promotes continued innovative work in space communications at JPL. Many thanks also go to the members of the planning and technical program committees as well as others who contributed their time and efforts in immeasurable ways.

We wish you all a productive workshop and, for the out-of-towners, an enjoyable stay in Pasadena.

Marvin Simon
Tsun-Yee Yan

Co-Organizers
IEEE CAS Workshop on Wireless
Communications and Networking

IEEE CAS Workshop on Wireless
Communications and Networking:
Power efficient wireless ad hoc networks
September 5-6, 2002, Pasadena, CA

http://dsp.jpl.nasa.gov/cas

Meeting Location – The workshop will be held at the Doubletree Hotel, Pasadena, CA, September 5-6, 2002.

Technical Presentations – There will be two plenary sessions on each day (one in the morning and one in the afternoon) as well as a poster session at the conclusion of each afternoon plenary session. Each presentation in the plenary session will last 30 minutes, including time for questions and answers. Prior to the first plenary session on each day will be a 45-minute keynote address. The plenary sessions will take place on the 2nd floor of the Doubletree hotel in rooms Fountain II and III. The poster sessions will also be on the 2nd floor in room Fountain IV.

Registration – The general registration fee is $350. For IEEE members the fee is $300 and for students the fee is $150. Discounts of $25 for students and $50 for others applied for early registration (prior to August 16). Registration will take place on the 2nd floor of the Doubletree hotel on Wednesday evening, September 4, from 6:00 p.m. to 9:00 p.m. and again on Thursday morning, September 5, from 7:00 a.m to 8:00 a.m. On Wednesday evening the registration will be held in the Santa Rosa Foyer and on Thursday morning the registration will be held in the Fountain Foyer outside the meeting rooms.

Welcoming Reception – There will be a welcoming reception from 6:00 p.m. to 9:00 p.m. on Wednesday evening, September 4. The reception is included as part of the registration fee and will be held on the 2nd floor of the Doubletree hotel in room Fountain III.

Workshop Dinner and Lunch – There will be a no-host cocktail party and dinner on Thursday evening and a lunch on Friday noon. These events will take place on the 1st floor of the Doubletree hotel in the Plaza room near the pool. The dinner and lunch are included as part of the registration fee. Guests may register for the dinner and welcoming reception at a fee of $50.

JPL Tour – A complimentary tour of the Jet Propulsion Laboratory is available on Thursday afternoon from 4:30 p.m. to 6:30 p.m. If you have already signed up for the tour through your response to our e-mail, transportation from the hotel to JPL and back will be provided. If you have not yet signed up for this tour and wish to go, please inquire at the meeting registration desk if space is still available.

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Thursday, September 5, 2002

Thu 08:00 – 08:30 Welcome and Opening Remarks:
Charles Elachi, Director, Jet Propulsion Laboratory, <celachi@jpl.nasa.gov>

Space and Earth Exploration 2010: Opportunities and Challenges: I will summarize past and current JPL missions in planetary, deep space, and Earth exploration; emphasize plans for future Mars exploration; and discuss in detail the needs and plans for future improvements to deep space communications, including an "Interplanetary Network".

Thu 08:30 – 09:15 Keynote Speaker: *Andrew J. Viterbi,* Qualcomm Co-founder, <andrew.viterbi@viterbigroup.com>

Science, Technology and Business of Digital Communication: While 19th century wireline and early 20th century wireless telegraphy systems already employed rudimentary digital communication, it was not till the middle of the 20th century that modern digital communication technology originated and it was not until late in the century that it blossomed. The impetus was two-fold: solid-state integration growing exponentially according to Moore's Law and the development of the system theories of information and communication. Together they rendered possible the sophisticated algorithms that enable efficient digital communications both via satellites and terrestrially. With origins in military and government satellite applications, these advanced communication systems became economically viable and universally available only in the 1990's. Digital satellite broadcasting and wireless cellular voice and data transmissions are the beneficiaries of this half-century of remarkable evolution.

Plenary Session 1: Low Power Design

Thu 09:30 – 10:00 Invited Talk – *Rajesh Gupta* – University of California, Irvine, <rgupta@ics.uci.edu>

Software Architecture for Low Power Management: Effective management of power in microsystems requires active participation of all the actors from applications to system software to network interfaces in making the right power/performance/quality choices. In this talk, I will describe results from our ongoing work on characterization of effectiveness of the power management algorithms and a software architecture that enables the application developer to turn the right hardware and subsystem "knobs" based on application context and dynamically changing performance/quality requirements. We provide software layers and functions to address two major energy-efficient techniques, namely DVS (Dynamic Voltage Scaling) and DPM (dynamic power management). We demonstrate the effectiveness of our software architecture by implementing power aware scheduling schemes within the *eCos* embedded real time operating system using realtime tasksets.

Thu 10:00 – 10:30 Invited Talk – *Rex Min, Manish Bhardwaj, Nathan Ickes, Alice Wang, and Anantha Chandrakasan* – MIT, <anantha@mtl.mit.edu>

The Hardware and the Network: Total-System Strategies for Power Aware Wireless Microsensors: The small battery capacity, ubiquity, and operational diversity of wireless microsensor networks create unprecedented energy management challenges. The energy consumption of microsensors is determined not only by the node's physical hardware, but also by the algorithms and protocols that impart functional demands on the hardware. We therefore present design methodologies that foster energy savings through collaboration across the hardware, algorithm, and network layers, in contrast to techniques that have explored only one of these spaces. For instance, dynamic voltage scaling is coupled with the intelligent distribution of within-network computation to extend latency deadlines and decrease supply voltages. The quality of communication is parameterized into metrics that drive the performance and energy consumption of the communication subsystem. Finally, the energy consumption of radios is carefully characterized to tune the efficiency of multi-hop routes. Collaboration between node software and hardware, and among the distributed nodes of the network, improves energy-efficiency and extends operational lifetime.

Thu 10:30 – 11:00 Invited Talk – *Subbarao Surampudi* – Jet Propulsion Laboratory, <ssurampu@jpl.nasa.gov>

Advanced Power Sources for Low Power Wireless Devices and Sensors: Advanced mobile wireless devices and sensor networks require power sources that are mass and volume efficient and can operate over a wide temperature range. Further these power sources must be able to be integrated with the wireless devices and sensors. State-of the art batteries and fuel cells are heavy and bulky and often times do not meet operation life requirements. This paper gives an overview of micro power sources such as micro fuel cells, micro thermoelectric devices and energy storage devices such as batteries and hybrid power sources that are under development.

Thu 11:00 – 11:30 *Pieter Op de Beeck, C. Ghez, E. Brockmeyer, M. Miranda, F. Catthoor, and G. Deconinck* – IMEC, Belgium**,** <pieter.opdebeeck@esat.kuleuven.ac.be>

Low-power Implementation of an OFDM based Channel Receiver in Real-time using a Low-end Media Processor: The implementation of advanced channel receivers using low-end multimedia instruction set processors is a productive, flexible and cost effective alternative to custom hardware. The stringent real-time and low-power requirements, typically found in receivers, become attainable by multimedia processors on condition that for these data-dominated applications the impact of the data transfer and storage related issues is first drastically reduced.

The focus of this paper is on the exploration of background data format alternatives for the implementation of a low-power channel receiver in real-time on the *Trimedia TM1300* processor. This multimedia processor is based on a VLIW instruction set architecture extended with sub-word level processing capabilities. The outcome of our approach is an optimized source code description of the channel receiver which optimally exploits the existing memory hierarchy while making use of the available sub-word acceleration instructions in a cost effective manner.

The transmission system in our application is based on OFDM modulation. Fourier analysis of the OFDM signal at the receiver side will produce the coded information symbols. In the reference code, a straightforward implementation of the standard [1, 2], the FFT computation kernel takes 57% of the total execution time, in total 3.7 seconds to output a 1 second input stream. This is clearly too slow to achieve real-time.

By following a data management oriented exploration methodology [3] we have been able to optimize the data transfer and storage related costs in a platform independent way. This new optimized code defines a second reference point where an 80% speed-up over the original reference is obtained. However the FFT function still takes a considerable 54% of the total time. To reduce the impact in energy and speed of such intensive computation kernel, the application of platform dependent optimizations have been considered. In concrete, several background data format alternatives for both an efficient utilization of the sub-word level acceleration capabilities as well as an optimal utilization of the memory caching mechanisms of the processor have been explored. In this way, the execution of the FFT computation has been reduced to become only 18% of the total application execution time, which itself has been sped-up by almost a factor of 2.

This gain can be attributed firstly to a reduction in memory accesses by 29%, which translates to 78% fewer system cycles (memory stall cycles), and secondly a reduction by 32% in CPU cycles (data, control and address processing) with respect to the platform independent code. The positive effect on CPU cycles is due to the sub-word parallel FFT code.

Since the final version of the channel receiver is only taking 0.37 seconds, the slack achieved in execution time makes it possible to lower the frequency, and thus the V_{dd} of the CPU core towards the minimum recommended by the processor's specification data sheet. In the *TM1300*, V_{dd} can be lowered from 2.5V to 2.0V [4]. This allows a 36% energy reduction in the CPU core while still running at real-time. However the most important source of energy reduction comes from the less activity in the memory hierarchy itself. Using a power model based on Cacti [5], and by accurately measuring the number of load/store operations executed and improved cache miss rate behavior, we have estimated that an 82% energy reduction has been achieved in the platform independent optimized version of the application code. This is reduced further to become only 12% in the final version after the exploration of platform dependent alternatives or likewise 3 times less energy consumption when compared to the platform independent reference.

References

[1] *European Telecommunication Standard ETS 300 401, Radio Broadcasting Systems; Digital Audio Broadcasting (DAB) to Mobile, Portable and Fixed Receivers*. RE/JTC-00DAB-4, May 1997, Second Edition.

[2] W. Hoeg and T. Lauterbach (editors), *Digital Audio Broadcasting: Principles and Applications*. J. Wiley and Sons, New York, 2001.

[3] F. Catthoor, K. Danckaert, C. Kulkarni, E. Brockmeyer, P.G. Kjeldsberg, T. Van Achteren, and T. Omnes, *Data Access and Storage Management for Embedded Programmable Processors*. Kluwer Academic Publishers, Boston, 2002.

[4] *Trimedia TM-1300 Media Processor Data Book*. Sept. 30 2000, Philips.

[5] <http://research.compaq.com/wrl/people/jouppi/CACTI.html>

Thu 11:30 – 12:00 *Ian D O'Donnell, Mike S.W. Chen, Stanley B.T. Wang, and R. W. Broderesen* – University of California, Berkeley, <ian@eecs.berkeley.edu>

An Integrated, Low Power, Ultra-Wideband Transceiver Architecture for Low-Rate, Indoor Wireless Systems: The characteristics of an indoor wireless sensor network, i.e. shorter transmit distances, lower bit-rates, a small footprint, and tight power consumption requirements, are well-suited to an ultra-wideband implementation. This form of transmission provides an alternative to conventional sinusoid-based radio that can co-exist with currently deployed narrowband systems if the transmission power is sufficiently low.

This paper describes the system architecture and circuit design implications of a proposed ultra-wideband network radio transceiver, targeting peer-to-peer communication at greater than 100 kbps over 5 meters with a goal of 1 mW total (TX+RX) power consumption. A narrow pulse (approximately 1 ns wide) is transmitted using simple digital switches, which spreads the energy over a Gigahertz of bandwidth. Reception, after gain and filtering, occurs in a bank of A/D converters which, after time alignment, captures the received pulse in a window 16 to 64 ns wide. This window is composed of 32 to 128 data samples at a 2 GHz rate and is repeated at the pulse repetition frequency of the input that ranges from 100 MHz to 1 MHz. The implementation issues of this system including the issues of clock generation, conversion bit-widths, gain, and the choice of pulse rate versus amplitude will be discussed along with the subject of interference.

Since the interference caused to existing narrowband systems is of critical importance, a system requirement was imposed that there would be negligible degradation of sensitivity for narrow band systems in the UWB band being used. This was estimated for a 2-dimensional array of UWB transmitters and the spectral limits for this "undetectable operation" will be presented.

Using this limit and a model of the interference to the UWB receiver from the narrowband systems, the receiver front-end specification is examined and system noise figure, gain, and A/D and matched-filter requirements are presented. From these results we find that a 1-bit A/D is adequate with 5-bit matched-filter coefficients and an additional spreading gain of 11 to 1024 chips. Power consumption is reduced by noting that the gain through the front-end only needs to be large enough to overcome the offset voltage of the 1-bit A/D (comparator). Also, to save more power, the wideband analog front-end circuitry may be turned off in the intervals between sampling windows.

Accurate generation of the timing signals is another critical part of the UWB system, since the jitter of the A/D sampling operation directly affects the sensitivity of the receiver. This jitter would best be minimized by using the highest possible, crystal-referenced, master oscillator frequency; however, this would require excessive power consumption. The considerations of the design of this oscillator will be given and how it affects the overall system performance.

The digital back-end processing implements a programmable pulse-matched filter, PN correlators, and simple acquisition and synchronization control logic that have a peak processing rate of 10 Mbit. Channel measurements influence the length of the pulse-matched filter needed to capture sufficient signal energy, and direct sequence spreading is employed to improve the symbol signal to noise. The area and power trade-offs versus acquisition time and matched-filter and correlation lengths will be given.

▸▸▸ *Plenary Session 2: Routing*

Thu 01:30 – 02:00 Invited Talk – *Massoud Pedram* – University of Southern California, <pedram@ceng.usc.edu>

Power-aware On-demand Routing Protocols for Mobile Ad Hoc Networks: Ad hoc wireless networks are power-constrained since mobile nodes operate with a limited supply of battery energy. To maximize the lifetime of these networks, network-related transactions through each node must be controlled such that the energy supplies of all nodes are exhausted at nearly the same time. This talk describes a number of source-initiated routing protocols for mobile ad hoc networks that achieve this objective and hence tend to increase the network lifetime. Network simulation results are presented and discussed at length.

Thu 02:00 – 02:30 Invited Talk – *Charles E. Perkins* – Nokia, <charliep@iprg.nokia.com>

AODV: Present and Future: Ad hoc networks are emerging as one of the most exciting research areas for new Internet technology development. Much of the recent effort has been focused on the development of routing protocols, but many more questions are becoming better understood and solutions envisioned. I will describe routing protocols proposed within the IETF with some emphasis on AODV, the Ad Hoc On-Demand Distance Vector protocol. Then, I will mention some of the problems that are receiving more attention recently, especially as discussed during the recent AODVng workshop which preceded MobiHoc this summer.

Thu 02:30 – 03:00 *Izhak Rubin and Arash Behzad* – UCLA, <rubin@ee.ucla.edu>

Cross-layer Routing and Multiple-Access Protocol for Power-Controlled Wireless Access Nets: Transmission power control in wireless communication networks is used to attain network throughput increase, energy conservation, or provide for quality of service (QoS) support. We consider ad hoc wireless networks that are configured as Mobile Backbone Networks (MBNs). A hierarchical network architecture is synthesized, consisting of Access Nets (ANets) and Backbone Nets (BNets). Each ANet is managed by (dynamically elected) Backbone Nodes (BNs) that are equipped with higher capability (transmission and processing) modules. The BNs are chosen from currently active mobile backbone-capable nodes, or are represented by (ground and or airborne) unmanned vehicles (UVs) that are guided into selected positions. In this paper, we investigate a combined cross-layer protocol for routing and multiple access (MAC) for an MBN access net (ANet). In an ANet, the user nodes are associated wit a BN that serves to allocate and manage their network layer (routing path) and MAC layer (time slot transmission) resources. Our new integrated protocol allows the net BN to instruct the ANet nodes to make power control adjustments while simultaneously allocating to them slots for the requested transmission of their packets. At the same time, a routing path is selected, so that a node may transmit its packet directly to the destination; or rather use the BN to relay this packet to a co-located destination node. Our algorithm employs a multitude of mathematical relationships derived by us for the underlying system that serve to simplify and reduce the computational complexity involved in the calculation of the resource allocation constraint set. We show this algorithm to lead to significant increase in the net throughput level through spatial reuse of the access net communications resources. Our scheme also strives to reduce power and energy requirements in that nodes only employ the power levels required to reach their designated destination (or next hop). Furthermore, the protocol tends to reduce employed power levels to achieve higher spatial reuse factors. In addition, through the use of resource (including time, frequency, or CDMA slots) allocations to identified user packet flows or real-time streams, we are able to provide quality of service guarantees to selected group of flows.

Thu 03:00 – 03:30 *Katayoun Sohrabi, William Merrill, Jeremy Elson, Lewis Girod, Fredric Newberg, and William Kaiser* – Sensoria Corp., <sohrabi@sensoria.com>

Scaleable Self-Assembly for Ad Hoc Wireless Sensor Networks: In distributed wireless sensing applications such as unattended ground sensor systems, remote planetary exploration, and condition based maintenance, where the deployment site is remote and/or the scale of the network is large, individual emplacement and configuration of the sensor nodes is difficult. Hence network self-assembly and continuous network self-organization during the lifetime of the network in a reliable, efficient, and scaleable manner are crucial for successful deployment and operation of such networks. This paper provides an overview of the concept of network self-assembly for ad-hoc wireless sensor networks at the link level, with descriptions of results from implementation of a novel network formation mechanism for wireless un-attended ground sensor applications using a multi-cluster hierarchical topology and a novel dual-radio architecture.

The goal of network assembly mechanism at the link level is to enable distributed formation of a connected wireless backbone and maintain this connectivity as the conditions in the network change, for example due to removal or addition of new nodes, over time. The network assembly is closely linked to the choice of the wireless channel access mechanism. We will briefly describe the fundamentals of this coupling. To ensure scalable operation of the network, a hierarchical network topology is preferred. This motivates a network self-assembly that generates a multi-clustered topology for a randomly deployed set of sensor nodes.

The multi-cluster mechanism enables the formation of a scalable network topology by allowing interconnected clusters in the network. Each cluster is formed independent of others, and is assigned a distinct channel. Certain nodes must be members of multiple clusters to allow network connectivity. This multi-cluster architecture enables the abstraction of the MAC dependent local channel operation so that each independent channel can be a fixed frequency, a TDMA schedule, or a CDMA spreading code, or even a local CSMA type channel on a fixed frequency. A node with a single radio must be switched between all the channels or clusters in which the node is a member of. This switching for most radios is not trivial, since it requires keeping accurate network synchronization on multiple channels in a serial fashion. For example, for frequency hopping radios, the transceiver must acquire the new code each time it switches to a different cluster. The switching time for some commercially available radios may be as high as 2-10 seconds. Also, for most commercially available radios, the level of access to radio firmware that will allow the type of channel switching required is simply not available. To alleviate the need for switching between clusters, a dual-radio node architecture was implemented where each radio is able to participate in a different cluster.

Simulation modeling of the multi-cluster self-assembly mechanism indicates that a dual-radio architecture is able to form large connected networks of size 400 and above in reasonable time intervals. The network self-assembly mechanism discussed here is part of a networking architecture that has been implemented on a hardware sensing platform. The mechanism has been demonstrated to work successfully using networks in excess of 10 nodes. Performance of variants of multi-cluster self-assembly in simulation and hardware implementation will be discussed.

Thu 03:30 – 04:00 *Cristina Comaniciu and H. Vincent Poor* – Princeton University, <ccomanic@ee.princeton.edu>

On the Capacity of Mobile Ad hoc Networks with Delay Constraints: Previous work on capacity characterization for ad hoc networks has focused primarily on source-destination throughput requirements for different models and transmission scenarios In [2], it was shown that the throughput for a fixed ad hoc network decreases like $1/(\sqrt{n})$ as the number of nodes (n) per unit area increases. This a consequence of the fact the number of required hops increases as $\sqrt{n}$. It was proved in [1] that, exploiting mobility improves capacity through a form of multi-user diversity, but at the expense of long transmission delays.

In this paper, we study the capacity of large mobile ad hoc networks carrying delay sensitive traffic. Because of tight delay requirements, we cannot take advantage of mobility as in [1]. We analyze the network given a stationary distribution of the mobile nodes' locations with constraints on the maximum number of hops between any arbitrary source-destination pair.

Using similar arguments as in [2] we show that limiting the maximum number of hops for any given transmission also improves the source-destination throughput by limiting the additional transmissions for the relayed traffic. On the other hand, this has a negative impact on the capacity by increasing the interference level. To enhance the network capacity we rely on advanced signal processing techniques such as multi-user detection, which can be implemented adaptively and blindly.

For system capacity derivation, we use results from random graphs theory [4]. A random graph is characterized by the number of nodes n and the probability of maintaining a link between two arbitrary nodes p. Using the results proved in [4] we can obtain a constraint on the probability of maintaining a link, such that the graph's diameter is d with high probability as the number of nodes goes to infinity.

As these results are asymptotic in nature we also validate them through simulations for finite values of n. The graph diameter represents the longest shortest path between any two nodes, and consequently, is the maximum number of hops required for transmission between any given pair of nodes.

The probability p characterizes the physical layer and it is defined as the probability that the signal-to-interference ratio can be maintained above the desired target. We compute p for different scenarios (CDMA with random spreading codes and matched filter, MMSE and de-correlating receivers) using an asymptotic analysis (both the number of nodes and the spreading gain are driven to infinity while maintaining their ratio constant). The randomness of the SIR is given by the random locations of the nodes.

We assume that the stationary distribution of the location of the interfering nodes is uniform within a disc of radius r (the range of the network) and the link gain decays according to a power law. Future results may also incorporate shadow fading.

For simplicity, we assume that all nodes transmit with the same power. Capacity results are obtained in terms of the maximum number of users that can be supported for given throughput requirements for any source-destination pair. We show that using adaptive multi-user receivers greatly improves the network capacity.

References

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▸ ▸ ▸ ***Poster Session 1***

Thu 04:00 – 05:30 *Martin Haenggi* – University of Notre Dame, <mhaenggi@nd.edu>

A Simple Power-Efficient MAC Scheme for Ad Hoc Networks: Channel access is a crucial issue for wireless ad hoc networks. While centralized schedulers achieve the best performance, their vulnerability and lack of scalability are serious drawbacks. On the other hand, distributed schemes perform sub-optimally but are robust and scalable. We propose a simple MAC technique that is fully distributed: in every timeslot, each node transmits with a certain probability p. This scheme can most easily be implemented and does not cause any overhead traffic. Despite its simplicity, it is useful for networks with stringent energy requirements. Its analysis also yields reference performance values that can be compared with more elaborate schemes that may be used in practice. It also provides guidelines how to choose the average backlog in ALOHA- or CSMA-type algorithms, where exponential backlogs may be used.

The analysis is based on a probabilistic model of the wireless link that encompasses noise, interference, and fading effects. Under Rayleigh fading, the signal-to-noise-and-interference ratio (SINR) that determines the success of a transmission is an exponentially distributed variable, which permits the separation of noise and interference effects. As a consequence, the SNR and SIR are independent random variables, and the performance analysis for the MAC scheme can be carried out separately for the transmit power P_0 and the transmit probability p. The probability of the successful reception of a packet is then the product of the probabilities that the SNR and SIR are bigger than a certain threshold.

The SNR is only affected by P_0, not by p. We can therefore consider a single link or point-to-point connection. Assuming that the application dictates a certain link reliability, the power consumption due to the transmit power level and due to retransmissions can be traded off. It turns out that the optimum value of P_0 is only 1.6 dB above the threshold times the noise variance.

The SIR strongly depends on the transmit probability p and on the large-scale path loss exponent. We show that for a network with N nodes, the expected throughput per timeslot as a function of p is a polynomial of order N, with zeros at $p = 0$ and at $p = 1$. The optimum is between 0 and 1/2. Small networks can be rigorously analyzed. We derive the throughput polynomial for one dimensional networks of up to 5 nodes (the one-dimensional case is important since every multi-hop connection in any network can be considered a one-dimensional network). For large networks, an asymptotical analysis shows that the per-node throughput converges to a constant. The useful range for p in the throughput-energy consumption trade-off is calculated, and we show that the optimum value in terms of energy results in a throughput that is 50% below the achievable maximum. For standard assumptions on the threshold and path loss, the maximum per-node throughput in a one-dimensional network is approximately 10%.

These results are derived for the case where only the average distance to the neighboring nodes is known. If a node knows the precise distances, it can adjust the transmit power to improve the energy efficiency.

Thu 04:00 – 05:30 *Vishal M. Ailawadhi and Gregory J. Pottie* – UCLA, <vishal@ucla.edu>

An Energy Efficient MAC Protocol for HANETs: As low-power, low-cost wireless devices become more sophisticated, capabilities of wireless networks will expand. Traditional wired networks, composed of primarily immobile units, will be augmented with untethered networks supporting a combination of stationary and mobile nodes. The absence of a wired infrastructure suggests that the network lifetime will be limited in cases where the replacement of energy reserves is either inefficient or impossible.

We present a MAC level protocol designed to provide energy efficient inclusion of mobile nodes within an energy-constrained stationary network. Networks of this configuration are defined as Hybrid Ad-Hoc Wireless Sensor Networks (HANETs). The stationary nodes are assumed to be randomly distributed homogeneous sensors which have already formed link-level connections, as well as a multi-hop routing structure leading to a sink node, without the aid of a central processing node. As mobile nodes are introduced into the stationary network, maintaining connectivity will decrease the energy reserves at the stationary nodes. The goal of the protocol presented here, therefore, is to allow the maintenance of link-level network connectivity while adhering to the energy constraints of the stationary network. Incorporating mobile nodes into HANETs begins with achieving connectivity to the stationary network. To accomplish this, the EAR protocol (Eavesdrop and Register) is presented. In taking into account the unique network architecture for HANETs, as well as the energy constraints at the stationary nodes, the question is posed as to whether the stationary nodes should be allowed to maintain control of handoffs within the network. The EAR protocol assumes a mobile-centric view of forming, maintaining, and breaking connections, as the mobile nodes are assumed to have fewer constraints on energy supplies as compared to the stationary nodes. A registry of possible stationary neighbors is formed at the mobile node, based on "Eavesdropping" the signals native to the stationary network's MAC protocols. Changes in received signal quality dictate the need for forming or severing connections. We define three new messages to supplement the stationary pilot signals to accomplish mobile handshaking and handoffs, of which only one will be attributed to the stationary nodes. Absolute handoffs are also defined, which, unlike relative handoffs, depends only the drop in the current connection signal quality below a predefined threshold. The high network density and close proximity of the stationary nodes suggests an ability to avoid acknowledgement messages, using timeouts to guarantee reception.

Using the EAR protocol in HANETs with a dense stationary wireless backbone network provides the ability to maintain a high quality of service in the face of mobility. Furthermore, there is nominal participation by the energy-constrained stationary nodes to maintain network connectivity for mobile nodes.

Thu 04:00 – 05:30 *Yunfeng Liang and Lian Yong* – National University of Singapore, <engp0536@nus.edu.sg>

A 250 MHz CMOS Bandpass Delta-Sigma Modulator using Continuous-time Resonator Structure: Bandpass delta sigma A/D converters perform direct conversion of a RF or IF narrow band signal to digital for processing and heterodyning in digital domain. The majorities of delta-sigma modulators in the literature are implemented as discrete-time circuits such as switch-capacitor or switch-current circuits. However, the speed of these modulators is limited, both by opamp bandwidth and by the fact that the circuit waveforms need several clock periods to settle. The idea of using continuous-time filters in delta sigma modulators was developed to relax the clock rate restrictions and in recent years clocking rates in the gigahertz range were reported. To achieve such a high speed data conversion, these modulators were realized using RF transistors such as in GaAs or InP technologies, and were hard to be integrated on the same chip with digital signal processing modules which are prevailingly realized in standard CMOS technology. On the other hand, attempts in CMOS bandpass delta sigma modulators are still limited to IFs of tens of megahertz. Here we report a 0.35um CMOS fourth-order bandpass continuous-time delta sigma modulator clocking at 1-GHz for direct conversion of narrowband signals located at 250 MHz.

The modulator presented here is based on two on-chip parallel LC tanks. The series connection of two second-order LC resonators yields a fourth order modulator. The integrated inductors have a quality factor as low as 1.5 at 250 MHz, so Q-enhancement transconductors are connected in parallel as negative resistors to cancel the positive resistance of the on-chip inductors. Due to the very low value of the inductor quality factor, the resonators realized by the LC tanks (together with the negative resistors) have a low pass term included in the numerator: $(As+B)/(s^2+w^2)$, instead of being purely band pass. In order to maintain full controllability of the continuous-time modulator to keep it equivalent to its prototype discrete-time design, the single-bit quantizer and latches are arranged in a one-digital-delay multi-feedback architecture. Both Return-to-Zero (RZ) and Half-delayed Return-to-Zero (HRZ) feedback waveforms are used to provide four tunable parameters. The feedback is implemented by current-summing with simple tunable current-switching DACs. The clock feed-through problem is solved by placing a swing-reduction driver before the current-switching DACs. Excess loop delay is compensated by a specially introduced delay in the clock signal. Metastability effects are mitigated by the one-digital-delay scheme which introduces two additional half-sample delayed latches in the feedback loop. These two additional latches provide the circuits enough regeneration time to resolve the quantizer input. Transconductors used in the modulator are based on the structure first proposed by Nauta in 1989 which is applicable for operation in VHF up to gigahertz.

The bandpass delta sigma modulator is implemented in a 0.35 μm triple-metal standard analog CMOS technology. The modulator occupies about 1.0 square mm, with the two on-chip inductors consuming about 60% of the total area. Post-layout simulation in CADENCE design environment with the simulator SPECTRE demonstrates the modulator achieves a 9-

bit performance in a 15.6 MHz bandwidth corresponding to an over-sampling ratio of 64. The clocking limit of 1 GHz is imposed by the quantizer circuit itself. If the same circuit is implemented in CMOS technologies with shorter channel lengths, the sampling rate limit can be pushed higher.

Thu 04:00 – 05:30 *Michael Angermann and Jens Kammann* – German Aerospace Center, Wessling, Germany, <michael.angermann@dlr.de>

Cost Metrics for Decision Problems in Wireless Ad Hoc Networking: Current and future mobile and portable devices e.g. smart phones or laptops are showing a clear tendency to incorporate not just one, but a multitude of wireless connection technologies per device. Many current phones have the ability to choose between standard circuit-switched data (CSD), high speed circuit switched data (HSCSD), general packet radio service (GPRS) and Bluetooth to transfer data. On Laptops, wireless LAN is often an additional alternative. If these devices are to connect to various networks in an ad hoc fashion to automatically perform tasks, efficient decision processes are needed to choose among these possibilities to optimize network usage and network availability both from the user and the system perspective. In conjunction with handover procedures, pro-active retrieval of data (pre-fetching) has the potential to reduce overall cost under frequently changing network conditions, despite the fact of an overall increased network load. Channels, timing and issued requests have to be carefully decided upon. We treat these decision processes as an optimization problem, for which suitable cost functions are needed. Typical metrics employed in fixed network scenarios, such as hop count are not well applicable in many wireless scenarios. Parameters like power consumption, call setup times, significant latency due to sophisticated channel coding methods and others are rarely addressed in previous network optimization research. In this paper we point out the requirements for useful metrics and propose sample cost-functions of system parameters that result in such metrics. In contrast to many research contributions that assume the optimization process to be situated in the network with overall knowledge of network state and traffic demand we investigate a decentralized optimization from the individual client perspective. We propose this as a reasonable approach for its technical feasibility, as it can be implemented in software in or on top of the mobile device's operating system.

We will present results derived from simulations at bit-, packet- and request/response level. An insight determined from these results is parameter sensitivity of the cost functions. The simulations are performed with dependent traffic sources for uplink and downlink in order to achieve meaningful results for the performance under typical request/response oriented protocols such as http.

Verifying the applicability of the proposed metrics and methods, as well as calibrating simulation parameters against measurements are the next important steps in our work.

The main contributions of the presented paper are an in-depth discussion of the special conditions existing for multiple wireless connection scenarios, reasonable structures for cost functions and optimized decision processes and a simulation to demonstrate the influence of the various parameters.

Thu 04:00 – 05:30 *Ignacio Solis, Katia Obraczka* – University of California, Santa Cruz, <isolis@cse.ucsc.edu>

ANA: Ad-hoc Nerve Addressing: Addressing in sensor networks has been left aside in current research. Most set up protocols have decided to assign random, probabilistically non-colliding, addresses to the nodes.

The address of a node is used for various purposes, namely to uniquely identify a node. In sensor networks, where nodes can loose individuality the scope of this unique identification can many times be reduced to one or two hop neighbors. Globally unique addresses for sensor networks are required for some tasks. We haven't yet established if the lack of point to point communications requiring unique addresses is due to the nature of sensor networks or to the lack of applications so far. The former seems to be the case but further proof is required.

We have also used addresses, and their structure, to aid us in routing. A clear example is how we used CIDR to minimize routing table entries. A completely random distribution of node addresses would make it impossible for the Internet to function since core routers wouldn't have enough resources to handle communication between two arbitrary nodes.

This work studies node address assignment in sensor networks and proposes ANA: Ad-hoc Nerve Addressing. We take advantage of the characteristics that define a sensor network and some of its possible scenarios. We consider sensor networks to be made up of mostly identical nodes, randomly deployed in a field communicating via wireless links. The objective is to devise an addressing strategy that will help with routing and energy conservation. Our main scenario deals with data gathering, either some form of environmental monitoring or specific events.

A principal data collector site, called the Central Nerve (CN), is the main point of communication of the sensor network. It can be though of as the most important node since it's the one that processes the information; relays it to the outside; or stores it. For example, in a planetary exploration the Central Nerve might be a major “lander” with antennas, relaying the information to a satellite.

Under this scenario, we expect most communication to originate or terminate at the Central Nerve, hence, we have developed an addressing scheme that is centered around it. Addressing nodes around other nodes is definitely not a new idea. Landmark routing is a clear base for our concepts as are similar wireless efforts.

Some of the things we consider and discuss include the traffic patterns (from CN, to CN, other), network dynamics (no mobility, low change), error conditions (node failure, packet drops), energy conservation, address length (fixed, dynamic), etc. We do not deal with security or MACs and we touch multicast only briefly.

We conclude with a description of the scenarios where ANA might be useful and what needs to be improved.

Thu 04:00 – 05:30 *Jeremy Elson, Lewis Girod, and Deborah Estrin* – UCLA, <jelson@cs.ucla.edu>

A Wireless Time-Synchronized COTS Sensor Platform Part I: System Architecture: Recent advances in miniaturization and low-cost, low-power design have led to active research in large- scale, highly distributed systems of small, wireless, low-power, unattended sensors and actuators [1]. While individual sensor nodes have only limited functionality, the global behavior of a sensor network can be quite complex. The network's value is in this emergent behavior: the functionality of the whole is greater than the sum of its parts. Such behavior is achieved, in part, through data fusion, the process of merging individual sensor readings into a high-level result.

Time synchronization is critical for data fusion, as it is almost always required to meaningfully correlate the output of distributed sensors with each other. There are many examples of sensor network tasks that require both synchronized time and known sensor locations: for example, to integrate a time-series of proximity detections into a velocity estimate [2]; to measure the time-of-flight of sound for localizing its source [5]; to distribute a beamforming array [9]; or to suppress redundant messages by recognizing that they describe duplicate detections of the same event by different by nearby sensors [6].

In Part I of two-part papers, we describe an implementation of a ad-hoc, distributed sensor platform that provides synchronized time to its users. By abstracting the time synchronization layer away, we allow developers to focus on the core challenges of their applications (e.g., signal processing, aggregation, routing) rather than dealing with the algorithmic and systems issues that inevitably arise when integrating sensing with distributed synchronization. Through a variety of techniques, most notably the use of Reference- Broadcast Synchronization (RBS) [3], our platform offers better than 5 JLSec precision when comparing streams of audio data acquired at peers separated by one hop.

Of course, time synchronization is a well-studied problem; for decades, protocols such as NTP [8] have kept the Internet's clocks ticking in phase. However, as we argued in [4], NTP is not necessarily the right choice for ad-hoc network. For example, NTP can exhibit poor behavior without the luxury of an infrastructure such as GPS [7], which provides an "out-of-band" common view of a single timescale to many places in the Internet. Without this common view, NTP is forced to pick a single clock as the master. With a only single master in the network, most nodes will end up being far away from it, and thus poorly synchronized to the global timescale. Even worse, nodes close to one another may end up with different paths to the master , making their errors uncorrelated.

Our platform is based on the Compaq iPAQ 3760, which is a handheld, battery-powered device normally meant to be used as PDAs. We selected the iP AQ because it is readily available, has reasonable battery life, supports Linux, and is usable right off the shelf. The iPAQ has a 137 MHz Intel StrongARM-1110 processor, 32 MB of RAM and 32 MB of FLASH for persistent storage. The iPAQ has a built-in speaker and microphone capable of sampling audio at 48 KHz. Using a PCMCIA-based wireless Ethernet card to implement RBS synchronization, our platform supports applications such as acoustic beam-forming by synchronizing a set of distributed audio codecs to within 5 msec-one quarter the sampling resolution.

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Friday, September 6, 2002

Fri 08:30 – 09:15 Keynote Speaker: *Deborah Estrin,* UCLA, <destrin@cs.ucla.edu>

Sensor Networks for Environmental Monitoring: Embedded Networked Sensi ng Systems, commonly referred to as sensor networks, will form a critical infrastructure resource for society -- they will monitor and collect information on such diverse subjects as plankton colonies, endangered species, soil and air contaminants, medical patients, and buildings, bridges and other man-made structures. Across this wide range of applications, Embedded Networked Sensing systems promise to reveal previously unobservable phenomena.

This talk will describe several motivating applications and outline some of the technical challenges posed by these long-lived, autonomous, massively distributed, and physically coupled systems. I will present several initial building block mechanisms that we and others in the community have implemented: such as time synchronization, adaptive-duty-cycle MAC techniques, and self-configuring topologies.

The last portion of the talk will introduce questions and possible solutions for the far less understood problem of how to manage distributed data storage and processing within the Embedded Networked Sensing system.

▸ ▸ ▸ *Plenary Session 3: Sensor Networks*

Fri 09:30 – 10:00 Invited Talk – *Parmesh Ramanathan* – University of Wisconsin, Madison, <parmesh@ece.wisc.edu>

Location-centric Approach for Collaborative Target Detection, Localization, and Tracking: In this paper, we describe the approach that the University of Wisconsin team has been pursuing for detecting, locating, and tracking ground based vehicles using sensor networks. The approach is based on the observation that signal processing for this application requires collaboration mostly among sensor nodes that in a small geographic region. Furthermore, it is not necessary for sensor nodes to be always active. Instead, results of collaborative signal processing in a geographic region can be used to wake up sensor nodes in other selected regions without jeopardizing the application goals. We have implemented and evaluated this approach on a network of Sensoria's WINS2.0 sensor nodes. Results of this evaluation will be included in the paper.

Fri 10:00 – 10:30 Invited Talk – *Jim Reich* – Palo Alto Research Center, <jreich@parc.com>

Collaborative Sensing and In-Network Processing of Sensor Network Data: I will discuss the challenges we have encountered and some of our solutions in implementing in-network processing on a sensor network for acoustic tracking of vehicles. Multisensor fusion for vehicle tracking in a centralized system is well-understood, but scales poorly in wireless networks with limited bandwidth and battery power. Performing the processing in-network, using local groups of collaborating sensors scales well, but presents a number of interesting algorithmic and protocol challenges. I will discuss these, with emphasis on sensor management: the selection of nodes to provide the best information available and the creation and maintenance of collaborative groups of nodes corresponding to specific physical phenomena.

Fri 10:30 – 11:00 *William M Merrill, Lewis Girod, Jeremy Elson, Katayoun Sohrabi, Fredric Newberg, William Kaiser* – Sensoria Corp., <williamm@sensoria.com>

Autonomous Position Location in Distributed, Embedded, Wireless Systems: While GPS is becoming ubiquitous for absolute position location in a wide variety of applications, in many systems alternative position location methods are desired due to GPS's sensitivity to jamming, its requirement for a clear view of the sky for operation, its accuracy, and its cost. This paper provides an overview of alternative geolocation mechanisms that may be used by embedded systems that only require relative position location, with a detailed description of results from one implementation using acoustic signaling.

Relative position location for embedded wireless distributed systems, unlike GPS, often do not require an external infrastructure, and may not need a global reference position. Discussion of the relative merits of active RF and acoustic signaling to determine range and/or angles between embedded wireless nodes is provided, as well as an assessment of current technology capabilities. Particularly, a comparison is made between time of arrival, angle of arrival, and path loss modeling methods to determine the relative locations of embedded wireless nodes, both via RF and acoustic signaling. Integral to this is an assessment of the capabilities required for the synchronization necessary in acoustic and RF time of arrival ranging. The severe impact of multipath signal propagation and dependence of signal path loss on environmental variation generally dictates the use of a time of arrival or time difference of arrival based methodology, either alone or in concert with another technique.

To demonstrate the capabilities of a relative position location system for wireless embedded nodes, details are provided on an implementation of a hybrid acoustic RF ranging technology. This technology leverages a RF wireless communications channel to provide inter-node synchronization, and RF coordination between nodes, while determining the distance between nodes through acoustic signaling. This acoustic signal consists of a chaotic sequence emitted from a speaker on each node and received on each other node in the system through its four microphones. The time of arrival at each microphone, synchronized over the RF channel with the acoustic transmit time, enables a range measurement at each microphone, which can then be used to triangulate the source position or reception angle. Collaboration between nodes over the RF channel is also accomplished to ensure reception of enough range and angle measurements to characterize the position of each node to a desired accuracy. Details are provided on the autonomous operation of this robust distributed system, which determines both angle and range between wireless nodes to provide an accurate relative position for each node. Details on the performance of this system in both indoor and outdoor environments are presented. Individual range accuracy on the order of 20 cm over tens of meters for tens of nodes is shown.

Fri 11:00 – 11:30 *Paul G Flikkema, Brent West, Bill Ruggeri* – Northern Arizona University, <paul.flikkema@nau.edu>

Network-Aware Lossless Source Coding of Spatio-Temporally Correlated Sensor Data: Wireless sensor networks for environmental monitoring have unusual characteristics and must meet a unique set of requirements. Data rates are extremely low, but limits on energy usage and total deployment cost dominate. Probably the most important metric is the average energy required to deliver a bit of information about the sensed environment to the destination. These networks also differ from the general case of ad-hoc wireless nets in that connectivity between two arbitrary nodes is not required, nor even desired; all that is needed is connectivity from each sensor to a controller or “home" node.

The particular application that we are targeting is the monitoring of microclimate variables, such as temperature, humidity and insolation (light intensity). Our goal is to provide an order-of-magnitude increase in spatio-temporal sampling over traditional non-networked sensing technologies, enabling significant improvements in models that will ultimately forecast ecosystem dynamics. The ultimate consumers of these data sets are scientists who desire the highest accuracy available. This in turn implies that lossless source coding for transmission through the network is required. Nonetheless, the high spatio-temporal resolution of the sensing implies a high correlation in both dimensions.

This paper describes a methodology for source coding of environmental sensor network data that exploits this correlation. While we wish to get close to the minimum number of bits required to represent the data,
we keep an eye on algorithmic complexity, as well as the trade-off between the achievable compression and delay.

It is well-known that in the general ad-hoc network case, nodes closest to a fixed home node carry the highest amount of traffic and are thus most vulnerable to energy depletion. Thus an important objective in this application is to find methods that minimize the rate of increase in information rate as a function of the network radius.

Our approach is a three-level model-based scheme. At the first level, the time series from a sensor is approximated by an adaptive polynomial function. The metric for this approximation is the minimum number of bits required to represent the approximation error for the worst-case data point. The second level is a fixed dictionary-based scheme based on the a priori statistics of the first-level approximation error. Each of these two levels is localized to an individual sensor. The third level exploits spatial correlation by allowing nodes along paths from more distant nodes to adopt existing model parameters to further minimize redundancy. We report in the paper both results using actual sensor network data and some key aspects of implementation in low-cost sensor nodes.

Fri 11:30 – 12:00 *K. Yao, H. Wang, L. Yip, D. Maniezzo, J.C. Chen, R.E. Hudson* – UCLA, <yao@ee.ucla.edu>

A Wireless Time-Synchronized COTS Sensor Platform Part II: Applications to Beamforming: Recent developments in integrated circuit technology have allowed the construction of low-cost small sensor nodes with signal processing and wireless communication capabilities that can form distributed wireless sensor network systems. These systems can be used in diverse military, industrial, scientific, office, and home applications [1-3]. In Part II of these two-part papers, we propose to perform beamforming based on coherent processing of acoustical waveforms collected from the sensor nodes for detection, localization, tracking, identification, and signal-to-noise-ratio (SNR) enhancement of acoustical sources, counting the number of such sources, and estimation of the impulse responses of the acoustical channels. In order to perform coherent processing of these waveforms, the signals collected from the nodes must be time-synchronized with respect to each other.

In the past, most reported systems performing these beamforming operations involved custom-made hardwares. In the paper, we propose to use Compaq iPAQ 3760s, which are handheld, battery-powered devices normally meant to be used as PDAs. We selected the iPAQ because it is small, has reasonable battery life, supports Linux OS, and is readily available commercial-off-the-shelf (COTS). Each has a built-in microphone and codec capable of sampling rate from 8 KHz to 48 KHz for acoustical acquisition. It can also support an 11MBit/sec spread-spectrum wireless Ethernet card for wireless communication. Each iPAQ is powered by a 206 MHz StrongARM-1110 processor and the memory includes a 32 MB ROM and a 64 MB RAM. The DSP capability of each iPAQ should be sufficient to perform the beamforming algorithms as described below.

Synchronization among the iPAQ's CPU clocks is achieved using Reference-Broadcast Synchronization (RBS), described by Elson et al in Part I of this paper. RBS periodically sends broadcast packets, recovering relative phase and frequency information by correlating the reception times of the broadcasts. On iPAQs, which have a clock resolution of 1 usec, RBS achieves a mean synchronization error of 1.26µsec ± 1.11 µsec.

Two of our previously proposed and verified beamforming algorithms [4-6] can be implemented on the iPAQ based sensor network as described in Part I of these two papers. The first class of beamforming algorithms exploits the time difference of arrivals (TDOAs) among the sensors. A blind beamforming method uses the maximum power criterion to obtain array weights from the dominant singular vector or eigenvector associated with the largest singular value or eigenvalue of the space-time sample data or correlation matrix. This approach not only collects the maximum power of the dominant source, but also provides some rejection of other interferences and noises. The relative phase information among the weights yields the relative propagation time delays from the dominant source to the sensors. Various forms of least-squares estimation methods are applied to these TDOAs to perform source detection, enhancement, localization, and delay-steered beamforming. The second class of beamforming algorithms uses maximum-likelihood (ML) parameter estimation method to perform source localization for near-field scenarios and direction-of-arrival (DOA) of the sources for far-field scenarios. Several sub-arrays yielding cross bearing DOAs can also be used to perform accurate source localization.

We compare the operations of these blind beamforming algorithms on the wireless sensor network. Complexity and performance of these algorithms vary greatly depending on the algorithms, type of sources, the geometric relationships among the sources and the sensor nodes, the signal strengths of the sources, and other system parameters. These system parameters include the time-synchronization errors in the sensor nodes, sampling rate of the iPAQ, etc. We will also compare the experimentally measured results with analytically derived Cramer-Rao Bounds (CRB) characterizing theoretical optimum performance as functions of SNR, time synchronization errors, and sensor node geometry. As we understand more of the real-time operations of this sensor network, our goal is to make the network to self organize and dynamically configure the needed sensor nodes to perform complex beamforming operations for various applications of interest.

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▸▸▸ *Plenary Session 4: Applications*

Fri 01:30 – 2:00 Invited Talk **–** *Jeffrey Foerster* – Intel Architecture Labs, <jeffrey.r.foerster@intel.com>

Ultra-wideband Technology Enabling Low-Power, High-Rate Connectivity: Ultra-wideband (UWB) technology has gone through some revolutionary changes this year, including the legalization of the technology in the US for imaging systems, vehicular radar systems, and communications and measurement systems. The allocation of 7.5 GHz worth of new, unlicensed spectrum that can be used for communications and measurement techniques, in particular, has sparked a renewed interest in both research and development of UWB technology in industry, universities, and government offices. However, a significant number of challenges remain for the technology to become ubiquitous. In this talk, I will present a brief status of the UWB industry, including international regulatory efforts that are currently underway, standards efforts that are being undertaken in the IEEE 802.15.3a study group, and some of the applications that are driving this movement towards both low-power, high-throughput capabilities as well as very low-power, low-throughput capabilities. Then, I will present some recent results and specific challenges for UWB physical layer designs for very high-throughput systems, which address narrowband interference and coexistence, multipath impairments, multiple access interference, and receiver complexity.

Fri 2:00 – 2:30 Invited Talk – *Gaurav Sukhatme* – University of Southern California, <gaurav@pollux.usc.edu>

Adding Actuation to Sensor Networks: Sensor networks could revolutionize our ability to harvest information from the physical world quickly, efficiently, planetwide. I will argue this in addition to sensing, communication, and computation, a fourth, very important capability is required to materialize this revolution: actuation.

I will describe some of the challenges and payoffs associated with introducing actuation into the mix, thereby extending 'conventional' sensor networks to sensor-actuator networks (or robotic sensor networks). Specifically I will focus on algorithms for localization and deployment which we have recently developed for such networks.

Fri 2:30 – 3:00 Invited Talk – *John J. Barton* – HP Labs, Palo Alto, <john_barton@hp.com>

New Opportunities for Wireless Technologies in Ubiquitous Computing: Over the past three years our research group in HP Labs Palo Alto has been working on applications in the emerging field of ubiquitous computing. Many of these applications use wireless networking. Unfortunately the properties of today's wireless technology fail to match the needs of such ubiquitous applications. I will review those aspects of our projects that suggest new requirements for future wireless technology.

Fri 3:00 – 3:30 *Peter Langendoerfer and Zoya Dyka* – IHP, Germany <langendoerfer@ihp-microelectronics.com>

A Low Power Security Architecture for Mobile Commerce: Third generation mobile phones and Bluetooth or W-LAN enabled PDAs offer easy and efficient access to the Internet. The aspect of mobility and the actual location of the service user make it possible to address new types of tasks. We are convinced that a whole set of (probably only locally available) applications which adapt their content to the user's location or other usage context will significantly gain popularity among the next generation mobile applications. These services will be developed on top of location-aware middleware platforms. Such platforms provide functions such as profile handling, positioning and location handling, event services etc. An example for such a service could be an "Airport Scout" that will guide you to your gate. Such a service could charge a certain amount of money per meter of the guided distance.

Privacy and security are of crucial importance when it comes to mobile-business. Encryption techniques can be used to ensure security and privacy. Public key encryption methods, which are definitely needed in this context e.g. for digital signatures, are computational intensive. The problems that arise are that all messages have to be encrypted in order to ensure privacy and that mobile devices have very limited resources in terms of calculation and battery power. The challenge here is to ensure privacy and security without a significant reduction of the up-time of the mobile device.

In this paper we propose a security architecture that exploits the imbalance of computational effort of the private and public key operations of RSA and elliptic curve algorithms (EC). In case of RSA public key operations require a significant smaller computational effort than private key operation whereas for EC it is the other way round. The basic idea now is to use an EC key pair on the mobile side and an RSA key pair on the platform side. The benefit of this approach is that the mobile has to execute only RSA public key and EC private key operations. Such a combination of these cryptographic approaches reduces the energy consumption of the mobile device up to a factor of eight if Koblitz curves over 2163 and ECDSA (Elliptic Curves Digital Signature Algorithm from NIST) are used for digital signature. Let's say the mobile has to generate its own digital signature as well as to verify the digital signature of the platform. Then, the energy needed for these operations is about two times less than those required with a pure EC key pair solution on Palm Pilot. In comparison with a pure RSA based approach the energy consumption drops down to one eighth. Additional energy savings can be gained since ECs provide the same level of security like RSA but with significantly smaller keys.

▸ ▸ ▸ Poster Session 2

Fri 3:30 – 5:00 *Alireza Hodjat, Ingrid Verbauwhede* – UCLA, <ahodjat@ee.ucla.edu>

The Energy Cost of Secrets in Ad-hoc Networks: Low energy security is a crucial requirement for wireless networks. The very first step in providing security to a wireless network is the key exchange and key agreement process. Symmetric or asymmetric techniques can be used for authenticated key exchange between parties in a wireless network. Protocols based on asymmetric-key encryption are the main solution for ad-hoc wireless networks because there is no need for a trusted third party in these algorithms. On the other hand, symmetric-key encryption techniques are applicable to the wireless networks with base stations. The main goal of this paper is to compare the energy cost of security for wireless ad-hoc networks versus non ad-hoc networks which use base stations as the trusted parties. In the case of wireless ad-hoc networks, the Diffie-Hellman key agreement protocol is used, while the Kerberos protocol is chosen for networks with base stations.

In a first step, well-known public-key and private-key encryption algorithms are implemented on the WINS wireless sensor node. These two are the Elliptic-curve public-key and Rijndael AES secret-key encryption algorithms. The energy consumption for these algorithms is measured for different data and key lengths. The results show that for Elliptic-curve point multiplication the average energy cost is 0.30, 1.07, and 2.34 Joules for 128, 192, 256-bit key, respectively. For Rijndael with 128, 192, 256-bit data and key the average energy consumption is 0.3, 0.55, 0.85 mJoules for encryption and 0.35, 0.65, 1.01 mJoules for decryption, respectively.

In the next step we explore the energy cost of some well-known key exchange protocols, such as the public-key Diffie-Hellman and the secret-key based Kerberos protocol and we examine their suitability for low power wireless networks, both ad-hoc and regular. A public-key Diffie-Hellman key agreement between two nodes will require four elliptic-curve point multiplication and two data transmission. On the other hand, if we assume that every base station implements a Kerberos server, in total four Rijndael AES encryption and four Rijndael AES decryption and six data transmission between the two communicating parties and their trusted party are used.

We compare the overall energy cost of key exchange process between parties in ad-hoc and non ad-hoc wireless network with the above protocols. These comparisons are done for different data and key length and different transmission power levels. The power consumption of the radio transmission on WINS varies from 0.37 Watt to 0.71 Watt with a transmission rate of 100kbps [NESL, UCLA]. As an example, the transmission of 256-bit data on maximum power level will consume 1.82 mJoules. The results show that the energy consumption of Elliptic-curve public-key cryptographic algorithm is three orders of magnitude larger than AES symmetric-key algorithm and the cost of communication. Therefore, adding transmission energy and encryption energy for different combination of data and key on a typical ad-hoc wireless network with asymmetric-key technique, still results in an energy cost which is two orders of magnitude larger than a non ad-hoc network with symmetric-key protocol. Therefore, providing security for ad-hoc wireless networks with public-key algorithms is not only harder than non ad-hoc wireless networks based on secret-key algorithms, but also it costs more energy.

Fri 3:30 – 5:00 *Budhaditya Deb, Sudeept Bhatangar, Badri Nath* – Rutgers University, <bdeb@cs.rutgers.edu>

A Topology Discovery Algorithm for Sensor Networks with Applications to Network Management: Sensor networks are randomly deployed collection of energy constrained sensor nodes with wireless communication capabilities. Management of sensor networks would be based on certain inference of network properties such as connectivity, reachability, coverage and usage patterns of various network resources. Network topology is an important model of the network state using which the above network properties can be inferred. In this paper, we propose an energy-efficient distributed Topology Discovery Algorithm (TopDisc) for sensor networks with its applications to data dissemination and aggregation, duty cycle assignments, etc. The Topology discovery is discussed from the perspective of sensor networks taking into consideration its statistical behavior and energy constraints.

The TopDisc algorithm utilizes the wireless Multicast Advantage [1] in sensor networks. Nodes can know the existence of other nodes in their communication range, just by listening to the communication channel. The algorithm takes advantage of this fact to find a set of distinguished nodes using whose neighborhood information we can construct the approximate topology of the network. A monitoring node that requires the topology of the network floods a topology discovery request to the network. During this flooding the set of nodes to respond back is chosen. Only these distinguished nodes reply back to the topology discovery probes, thereby reducing the communication overhead of the process. These distinguished nodes form clusters comprised of nodes in their neighborhood. These clusters are arranged in a tree structure called TreC, rooted at the monitoring node (or the initiating node).

The TreC represents a logical organization of the nodes and provides a framework for managing sensor networks. Using only local information between adjacent clusters, information flows from nodes in one cluster to nodes in a cluster at a different level in the TreC. The clustering also provides a mechanism to assign node duty cycles such that a minimal set of nodes are active in maintaining the network connectivity. The cluster heads incur minimal extra overhead of setting up the structure and maintaining local information about its neighborhood.

TopDisc selects a set of nodes such that all nodes in the network are either part of this set or neighbors of this set. Thus it essentially finds a dominating set of nodes for the network. Many algorithms exist for finding dominating sets for networks. However TopDisc is desirable because of the following factors.

- The dominating set is created using message complexity of N (number of nodes in the network), i.e. each node sends only one packet. The performance of TopDisc to find this set is similar to a centralized greedy $\log(N)$-approximation scheme. Such a leader election algorithm using only one packet per node makes it very useful for energy constrained sensor networks.
- TreC formed is optimal in the number of hops from monitoring node. Thus if any node is actually h hops away from the monitoring node, it is also h hops away from the monitoring node in the TreC. Thus the topology response packets travel the minimal number of hops as topology is aggregated along the TreC. The node at the center is the monitoring node for the network.
- The above characteristics are achieved using local timer mechanisms to forward topology discovery request packets and select the responding nodes.The timer mechanism actually makes it possible to do the above using only one packet per node. The timers are based completely on local information and do not require any time synchronization. Hence it is very practical for sensor networks.
- The cardinality of the responding node set is dependent only on the network dimensions and communication radius and is almost constant with respect to density. Thus for a given network dimension and communication radius, the overhead of TopDisc is almost constant even though the density increases.
- TopDisc provides the reachability map for the network and can be used for resource discovery since all active nodes can be reported using TopDisc. Although the retrieved topology is only aproximate, it maintains some bounds on path lengths if used for routing. For example, if any node is h hops away from the monitoring node in the actual graph, it is at most $h+2$ hops in the topology retrieved by TopDisc.

Please refer to the technical report of this work [2] for details of the paper.

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Fri 3:30 – 5:00 *Richard Han, Anmol Sheth* – University of Colorado at Boulder, <rhan@cs.colorado.edu>

Adaptive Distributed Transmit Power Control in 802.11b Ad Hoc LANs: A standard approach for reducing power consumption among communicating mobile devices is to lower the transmit power to the minimum level that still achieves correct reception of a packet despite intervening path loss and fading. In a prior submission currently under review, we adopted this minimization approach and described an implementation of adaptive transmit power control for 802.11b ad hoc wireless networks. While previous work by other authors had focused on simulation and theory, our work focused on implementing distributed adaptive power control in an ad hoc 802.11b system, enabled by the introduction of 802.11b cards with adjustable transmit power levels, e.g. Cisco Aironet 350's. Our design employed an application-layer approach, which enabled application transparency, incremental deployment, and media independence, i.e. Bluetooth and RF-based sensor networks will also benefit from this algorithm in addition to 802.11b-based networks. In addition, our protocol adaptively adjusted its transmit power in a bandwidth-efficient manner in response to mobility and variations in received signal strength (RSS) due to multipath.

In this paper, we focus on work in progress motivated by our earlier experiences with adaptive power control. First, we explore mechanisms for improving adaptation to mobility. A beneficial property of a transmit power control protocol is that it adapts to motion, increasing (decreasing) the transmission power as the receiver moves further away from (closer to) the sender. Our initial design employed a fixed threshold of +/- 2 dBm for determining when the received power had changed "significantly" enough to trigger a signal to the sender to reset its transmit power. In addition, our initial design employed a fixed cushion of 3 dBm above the computed optimal transmit power (equal to path loss + time-averaged RSS), to avoid false triggers caused by multipath-induced RSS variation. In this paper, we employ adaptively smoothed estimates for both the cushion and the trigger threshold, improving upon our initial approach in much the same way that TCP's congestion control algorithm evolved.

We also address a new twist to the familiar wireless hidden terminal effect introduced by heterogeneous transmission powers and radii. When nodes in an ad hoc network are allowed to modulate their transmission power, it is possible that a node falsely senses the channel to be free during an RTS/CTS exchange. In a constant power scenario, a node responding to a CTS will disable all nodes within a fixed known radius. However, a node whose transmit power has been optimally lowered will respond with a CTS with a far smaller radius. As a result, another node *N* with a larger transmission power may not hear the weaker node's CTS, resulting potentially in more collisions when *N* unwittingly transmits. We explore solutions for such scenarios in this paper, including transmitting the RTS/CTS control packets at the maximum transmit power and adding an additional control frame to the existing 802.11b protocol, and evaluate the tradeoffs between power consumption and interference.

In addition to the set of 802.11b-enabled laptops, we also implemented the protocol over a set of Berkeley/MICA wireless sensor Motes.

Fri 3:30 – 5:00 *Arindam K Das, Robert J. Marks II, Mohamed El-Sharkawi, Payman Arabshahi, Andrew Gray* – University of Washington and the Jet Propulsion Laboratory, <arindam@ee.washington.edu>

The Minimum Power Broadcast problem in Wireless Networks: An Ant Colony System Approach: Broadcasting/multicasting in wireless networks is fundamentally different as compared to wired networks, since multiple nodes can be reached by a single transmission. This, of course, assumes that the nodes are equipped with omnidirectional antennas, so that if a transmission is directed from node *i* to node *j*, all nodes which are nearer to *i* than *j* will also receive the transmission. This is known as the "wireless multicast advantage" [1]. For a given node constellation with an identified source node, the minimum power broadcast (MPB) problem in wireless networks is to communicate to all remaining nodes, either directly or hopping, such that the overall transmission power is minimized.

Although previous work in this area focused on a "link-based solution"', Wieselthier et al [1] note that a "node based" approach is needed for wireless environments. The broadcast incremental power (BIP) algorithm suggested by them for constructing the minimum power broadcast tree is a "node-based" minimum-cost tree algorithm for wireless networks. In this algorithm, new nodes are added to the tree on a minimum incremental cost basis, until all intended destination nodes are included. Other approaches suggested recently for solving this problem include an internal nodes based broadcasting procedure by Stojmenovic et al [2] and an evolutionary approach utilizing the "viability lemma" by Marks et al [3]. In this paper, we describe a swarm intelligent approach for solving the MPB problem.

Swarm intelligence appears in biological swarms of certain insect species. It gives rise to intelligent behavior through complex interaction of thousands of autonomous swarm members. Interaction is based on primitive instincts with no supervision. The end result is accomplishment of very complex forms of social behavior and fulfillment of a number of optimization and other tasks [4].

The main principle behind swarm intelligence interactions is stigmergy, or communication through the environment. An example is pheromone laying on trails followed by ants. Pheromone is a potent form of hormone that can be sensed by ants as they travel along trails. It attracts ants and therefore ants tend to follow trails that have high pheromone concentrations. This causes an autocatalytic reaction, i.e., one that is accelerated by itself. Ants attracted by the pheromone will lay more pheromone on the same trail, causing even more ants to be attracted. In essence, therefore, swarm intelligence paradigms use positive reinforcement as a search strategy.

The Ant Colony System (ACS) algorithm, a swarm based optimization procedure, was first proposed by Dorigo and Gambardella [5] for solving the celebrated traveling salesman problem (TSP). Experimental results indicate that the ACS algorithm outperforms other evolutionary techniques like simulated annealing, elastic nets and self-organizing maps on the TSP.

The ACS procedure we propose and describe in the paper for solving the MPB problem uses a mix of narrow vision and wide vision ants. We assume that all ants have complete knowledge of the locations of the nodes in the network. While a narrow-vision ant located at node i tends to choose a nearby unreached node to visit next, wide-vision ants are allowed to choose distant nodes to visit next. Wide-vision ants are therefore less greedy than the narrow-vision ants. Simulations indicate that wide-vision ants, with their less greedy approach, are generally better able to exploit the "wireless multicast advantage" during the initial exploration phase of the algorithm. The narrow-vision ants, on the other hand, are generally more effective during the latter stages of the algorithm when they hone in on the best routes generated by the wide-vision ants and look for better solutions within local neighborhoods. Based on this observation, we have incorporated a dynamic ant population in our algorithm such that, while most of the ants initially start out as wide-vision ants, they are allowed to gradually adopt a greedier strategy and ultimately end up as narrow-vision ants. Experiments indicate that a dynamic ant population is generally able to produce better solutions and converge faster.

Simulation results on 50 randomly generated 10-node networks show that the average tree power of the solutions generated by our procedure is approximately 11% less than the average tree power obtained using the BIP algorithm. Similar experiments on 50 randomly generated 50-node networks show an improvement of about 14% on the BIP algorithm. While 10 ants and 50 iterations were used for the 10-node experiments, 25 ants and 100 iterations were used for the 50-node experiments.

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Fri 3:30 – 5:00 *Sascha Slijepcevic* – UCLA, <sascha@cs.ucla.edu>

Error-Tolerant Multimodal Sensor Fusion: Embedded sensor network (ESN) is a system of nodes, each equipped with a certain amount of sensing, actuating, computational, communication, and storage resources. ESN is one of the prime candidates for widely used ubiquitous computing system that will bridge gap between the computing and physical worlds. One of the most important generic ESN tasks is multimodal sensor fusion, where data from sensors of different modalities are combined in order to obtain better information mapping of the physical world. One of the key prerequisites for all ESN applications including multimodal sensor fusion, is to ensure that all of the techniques and tools are error and fault tolerant while maintaining low cost and low energy consumption.

We first address the problem of multimodal sensor fusion (MSF) by developing two generic schemes that are sufficient to solve the MSF problem for a majority of common types of sensors. The first scheme assumes binary sensors; the second considers multilevel sensors.

The generic MSF approach has two phases. In the first phase, we build combinatorial or analytical model of the world that uses as the inputs (parameters) sensor data. In the second, we use the traditional optimization techniques to figure out which data has to be altered so that the model is consistent. Specifically, the goal is to alter as few as possible pieces of data on as few as possible sensors. The underlying assumption is that a majority of sensors that record consistent data are most likely functioning properly and that their data can be used to calculate (or correct) through the developed models data provided by other sensors.

For the case of binary sensor we formulated the sensor resource allocation (SRA) problem in the following way.

INSTANCE: Set A_1 of points p (x_{i1}, ...,x_{im}), in m-dimensional space, a positive integer J_1, set H that consists of $m(n-1)$ [m-1]-dimensional hyper planes that are perpendicular to one of the m axes, such that each hyperplane is separating two points p_i and p_j that have the closest coordinates along the axis to which the hyperplane is perpendicular.

QUESTION: Find a subset of selected hyperplanes H, such that any two points p_i and p_j are separated by at least one of the selected hyperplanes and also the cardinality of H is at most J_1.

We proved that is NP-complete. We also have developed two algorithmic engines to solve the RSA problem: ILP-based and maximally constraint minimally constraining heuristic. Experimental results indicate high quality of the heuristics.

Probably the best way to introduce our MSF approach for multilevel sensors is to take a closer look at an example. We have an object *O* that moves along its trajectory that includes points p_i in embedded sensor network that consists of a number of nodes. We assume that we have four types of sensors: RSSI-based or acoustic signal-based distance discovery, speedometer, accelerometer, and compass that are used to measure the angle in 2D physical space. Three distance measurements can be used to locate the object *O* in any particular moment. Euclidian space, Newton mechanics, and trigonometry laws can be used to establish relationships between measurements of different modalities.

From these equations, we can calculate for each variable, how much it has to be altered in order to make the whole system of equations maximally consistent. Note that the variables that have to be altered the most are most likely measured by faulty sensors. For example, one way to identify and correct sensor measurements is to try all scenarios where exactly one type of sensor measurements is not taken into account and compare the maximal error in the system. The preliminary experimentation results indicate that the approach is very efficient and robust.

Fri 3:30 – 5:00 *Miodrag Potkonjak* – UCLA, <miodrag@cs.ucla.edu>

Power Minimization by Separation of Control and Data Radios: Sensor networks have recently attracted a great deal of research attention due to their wide range of applications including military, education, monitoring, retail, and science. Most sensor networks system use battery as the source of energy. Due to the persistent technological battery limitations, most often the sensor nodes must operate on an extremely frugal energy budget. In majority of sensor network applications and architectures, communication cost dominates the energy budget. Therefore, there is strong need for reducing radio related power consumption.

Recently a number of experimental studies have been conducted and identified a variety of effective ways for radio power reduction in wireless ad-hoc sensor networks. For example, in a recent patent, Motorola proposed the idea of incorporating two radios in a single sensor node: one is high power, high bandwidth; and the other one is low power. The first radio is responsible for carrying out the communication operations such as transmitting and receiving data from other nodes. It is power hungry, meaning that it is a main energy consumer once it is operating. However, it is often in the sleep/off mode unless there are needs for it to be awakened. A low power-consuming radio is often operating and its only responsibility is to wake up the communication radio when it is necessary to transmit data.

Partly inspired by this idea, and partly by data/control separation in computer systems, we propose a new approach that in a sense provides further push for the state-of-the-art of how to employ the two-radio strategy that has significant advantages. We also adopt the two-radio approach: one is high power, high bandwidth and one is small bandwidth, (symbol rate) and low power. In our approach, the second radio is not just responsible for waking the high power radio, but also for conducting all control related tasks. These tasks are characterized by low symbol rate and high frequency of occurrence. For example, information about the current sleep policy, estimated bandwidth needs, storage buffer occupancy, and the detection of rare events are all being conducted using the low power radio. On the other hand, data radio is only responsible for transmitting and receiving high volume sensor data. It is used in bursts and often only for a relative short period of time. Since the waking radio is very energy consuming, significant savings can be achieved.

The advantages of data, and control streams of data, in wireless networks provides not only lower power consumption, but also a better fault tolerance. The energy being consumed by the data radio is even lower than it does in the original scenario because the reduction of its operating time to transmit short control packets. Fault tolerance is also being increased because is some situations the control radio can be used to carry out sensor data. The key design trade-off of this new approach is how to design each radio and properly size them. In addition, we have developed a new sleep policy and power (signal strength) management scheme for the sensor networks that use these new two-radio sensor nodes. We are currently implementing simulation models to evaluate and quantify the potential benefits of new scheme.

Fri 5:00 – 6:00 Panel Discussion

- *Ken Wolfenbarger* (Moderator) – Jet Propulsion Laboratory
- *Son Dao* – HRL Laboratories
- *Lakshman Krishnamurthy* – Intel Architecture Labs
- *William Kaiser* – Sensoria Corp.
- *Charles E. Perkins* – Nokia
- *Jim Reich* – Palo Alto Research Center

Commercial Interests in Wireless Ad hoc Networks: This 1 hour panel will discuss commercialization opportunities and barriers related to launching a global ad-hoc wireless network. People often compare such a network with existing cell phone infrastructure. Part of the challenge of large scale deployment of this technology is that it requires consumers to “cooperate” in order for the system to work. This is in contrast to launching a satellite and encouraging the consumer to “plug-in” for service. The panel will attempt to address the issue of whether the consumer needs this new technology; for what applications it might be needed; and if there is an “easy” niche market for such a network. The panel will also debate the technological advances that make such a network possible today but not say ten years ago. From the discussion you will come away knowing the top challenges that could prevent this technology from being commercialized today. If time permits, the panel will touch upon the viability of the latest Ultra Wide Band technology (UWB) as a link media for such a network.